# Weight of Evidence and Path Analysis Applied to the Identification of Causes of the Cherry Point Pacific Herring Decline

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## Introduction

A classic problem in environmental decision making is the estimation of the causes of impacts observed in aquatic populations and communities at regional scales. I applied a weight of evidence (WoE) and path analysis approach based upon our relative risk model in order to estimate the cause of the decline of the Cherry Point Pacific herring. This WoE approach is based upon a risk assessment type conceptual model in order to link the paths of potential sources of stressors to the effects seen in the population. Ranking criteria and regressions are used to assign weights to the potential sources and stressors. A Monte Carlo analysis is applied to represent the uncertainty in each of the ranks, correlations and filters and to estimate the uncertainty of the analysis. This technique results in a series of multinomial distributions representing the likelihood of a stressor causing an impact. In the case of the Cherry Point herring, climate change, habitat alteration and contamination at a landscape scale were identified as important stressors. This case study demonstrates that a clearly derived and quantified WoE and path analysis is a useful approach to investigating casual links at regional scales.

## Cherry Point Herring History

The Pacific herring stock that spawns at Cherry Point, west of Bellingham, WA, has undergone a dramatic decline in the last 20 years. The Cherry Point region has associated with it two oil refineries and an aluminum smelting operation. Fishing for herring roe and eggs has occurred in the past, but is now banned in the region. Our charge from the Washington State Department of Natural Resources was to evaluate the risk factors to Herring posed by the Cherry Point region in order to manage the site. An additional charge was to evaluate alternative resident endpoints as tools for resource managers for managing the region.

We conducted a regional ecological risk assessment using the relative risk model (RRM) to investigate the causes of the current decline, current risks to the population, and the outcomes of future management options. The RRM incorporates geographic location and multiple anthropogenic and natural stressors into estimating risk. The population decline of the herring, corresponds with a collapse of the age structure, although survivorship of eggs to the age 2 class has not diminished. The range of spawning areas has also declined, with the area of Point Whitehorn as the principal location.

The retrospective risk assessment identified climate change, as expressed by the warmer sea surface temperatures associated with a warm Pacific Decadal Oscillation (PDO), and exploitation as important risk factors. The warmer water also changes patterns in food resources, predators, and water quality. Contaminants have the potential for impact, but exposure to the eggs, hatchlings and fry has not been demonstrated at Cherry Point. Exposure to contaminants to adults during migration may occur and has been included into our assessment. Modeling of the population age versus fecundity curves and survivorship data indicate that the current population of age 2 and 3 fish can not be self sustaining without the survivorship or immigration of age 4 and older fish.

The difficulty with the retrospective analysis is that it is very difficult to quantify the uncertainty with these type of procedure. In order to better describe the uncertainty with the assignment of probable cause it is important to investigate other methods. The weight of evidence (WoE) approach as outlined by Menzie et al (1996) is a promising approach.

## Weight of Evidence

Classic methodologies such as Hume's criteria and Koch's postulates do not work well for open systems with diverse symptoms. The open system and the large scale associated with sites such as Cherry Point preclude experimentation. Large scale factors such as the PDO are not possible to manipulate and must be incorporated into any causal framework. Eco-epidemiological approaches such as Suter, Norton and Cormier (2002) are not inherently quantitative but rely on scoring schemes that are not easily manipulated mathematically and that do not incorporate uncertainty. The quantification of the scoring scheme and the express statement of uncertainty are both important factors in a useful means of assigning causality.

A retrospective assessment coupled with a modern idea of scale, weight of evidence approach and uncertainty analysis can produce a quantitative framework for ranking risk factors. The next paragraphs describe how the relative risk model was modified for a retrospective assessment incorporating Monte Carlo analysis to describe uncertainty.

**Introduction to the Relative Risk Method (RRM)**
The RRM was developed during our ecological risk assessment of Port Valdez, AK. Like this study area, Port Valdez has a variety of anthropogenic stressors including fish hatcheries, fish processing wastes, petroleum-based effluents from the pipelines, municipal effluents and tanker traffic (Landis and Wiegers 1997, Wiegers et al. 1998). The variety of stressors and endpoints led Wiegers and colleagues tot he source-habitat-impact model for conceptual model development.

**Source-Habitat-Impact**
In a regional multiple-stressor assessment, the number of possible interactions increases exponentially. Stressors arise from diverse sources, receptors are associated with a variety of habitats, and one impact may lead to additional direct and indirect effects. The approach of our current regional assessment model is to identify the sources and habitats in different locations (risk regions) of the Cherry Point coastal system, rank their importance in each location, and combine this information to predict relative levels of risk. The number of possible risk combinations resulting from this approach depends on the number of groups identified in each risk region. For example, if two source types and two habitat types are identified, then four possible combinations of these components can lead to an impact. If we are concerned about two different impacts, eight possible combinations exist.

**Use of ranks and filters to quantify relative risk.** Our regional approach incorporates a system of numerical ranks and weighting factors to address the difficulties encountered when attempting to combine different kinds of risks. Ranks and weighting factors are unit-less measures that operate under different limitations than measurements with units (e.g., mg/L, individuals/cm$^2$). We link these ranks to specific locations within a landscape, providing a map of risks with the sources of risk clearly identified.

**Spatially explicit.** Sources and habitats are specifically included in the risk assessment, making it spatially explicit. Risks can be defined for specific areas, within the context of the entire region. Gradients of risk may exist, due to the presence of a variety of stressors generated by a variety of sources. The relative risks can be mapped and decisions made at a regional level.

**Use in a prospective and retrospective approach.** Previously published studies include examples of prospective risk assessments where future impacts are calculated. In a retrospective risk assessment the goal is to identify stressors and the sources that have contributed to an observed historical impact in that environment. The process reverses the normal order of consideration from source-habitat-impact to impact-habitat-source.

**Common ranking methodology.** The numerical scores that are obtained in the ranking process are unique to the set of decisions and ranking criteria derived for that specific region. The numerical scores can not be compared directly to other studies or regions unless a set of newly derived scoring procedures are derived. If several areas are being compared in order to set remediation or management priorities, then each area needs to be combined into a single RRM setting. This approach provides the setting for the analysis of the cause of the decline of fishery.

## Retrospective WoE analysis for Cherry Point Pacific Herring
The basic conceptual model for the Cherry Point Pacific herring has been published (Landis et al in press) and has been adapted for this retrospective analysis (Figure 1). The conceptual model incorporates each of the sources providing the stressors linked to the observed impacts in the population. A simplified model that deals only with the source climate change is presented in Figure 2.

Climate change is the source of the change in temperature within the northeastern Pacific Ocean known as the Pacific Decadal Oscillation (PDO). Climate change is also a source of habitat alteration as species migrate due to alterations in conditions. Predators may increase or decrease in number, nutrient fluxes can be altered, and the distribution of prey items altered. Disease may also be an important issue as new pathogens may be brought in by the change in conditions. In the simplified model there area total of 13 interactions that must be considered.

The next stage is that the evidence for each source, stressor and potential linkage is examined and provided a rank. In this instance the ranks are based upon Landis et al (2002; in press). The next step is that the available information is then used to assign a distribution to each rank depending upon the uncertainty associated with each factor.
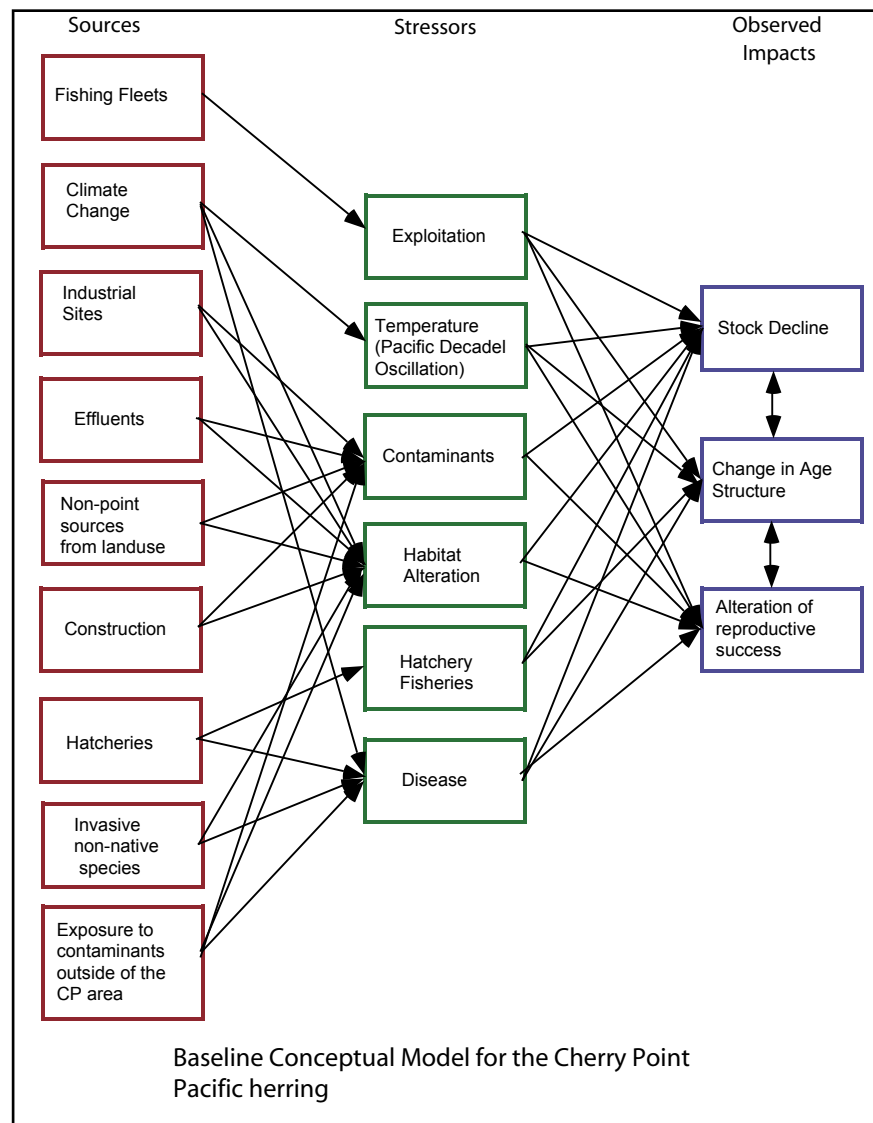
**Figure 1.** Conceptual model for the WoE approach to determining the likely cause of the stock decline at Cherry Point, WA.

After the assigning of distributions a Monte Carlo analysis is performed using Crystal Ball® 2000 software as a macro in Microsoft® Excel 2002. I ran the Monte Carlo simulations for 1,000 iterations and derived output distributions for each sub-region, source, habitat and endpoint risk prediction. The distributions depict a range of probable risk estimates associated with each point estimate. After running preliminary simulations of up to 10,000 iterations, 1,000 iterations appeared sufficient and resulted in similar results. This procedure allows me to estimate the resultant uncertainty in the retrospective analysis. The next paragraphs provide examples of each step.

Figure 3 illustrates the distribution selected to represent the uncertainty for three variables. In the case of fishing fleets as a source there is a great deal of documentation that fishing upon herring, both at large scales and upon the spawning fish, has occurred. The uncertainty is in the fact that it is not clear what amount of off shore fishing has directly affected the Cherry Point Pacific herring and how much has been on stocks that are not related. In this case a rank of 6 is the preferred input, probability of 0.80, but a rank of 4 is also given a set probability (0.20).

An intermediate case is effluents. Effluents are common throughout the Georgia Straits and Puget Sound region, but the toxicity is not generally high and rapid dilution occurs because of the magnitude of the currents in the region. However, local high concentrations from industrial sources or untreated stormwater run-off could be damaging. In this instance the most common rank is a 4, with ranks of 2 and 6 given a lower probability.
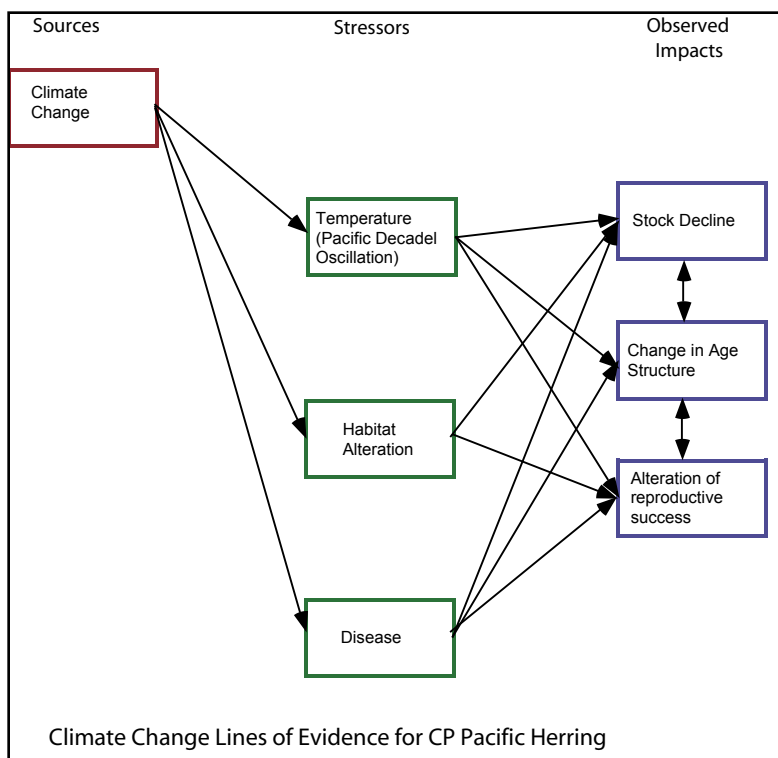
**Figure 2.** Simplified conceptual model identifying the links due to Climate Change as the Source of the stressors.
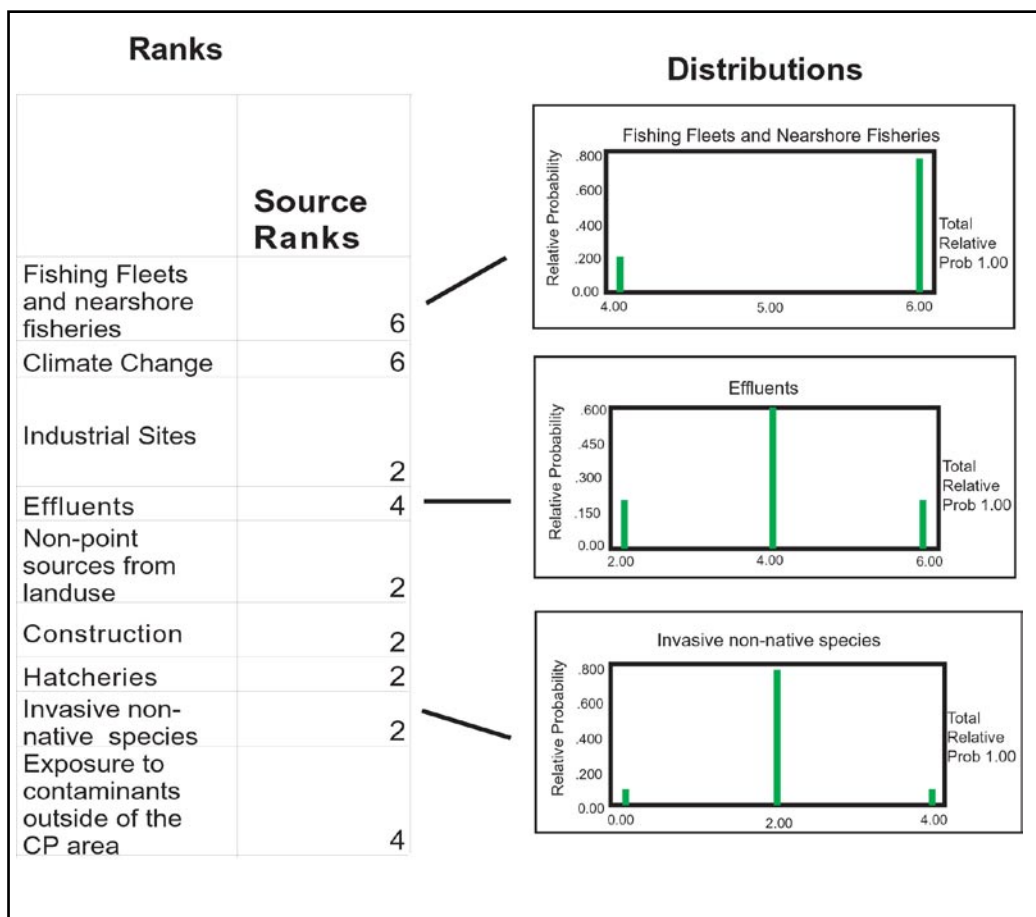


**Figure 3**. Example of how distributions are established for the various ranks in the conceptual model.
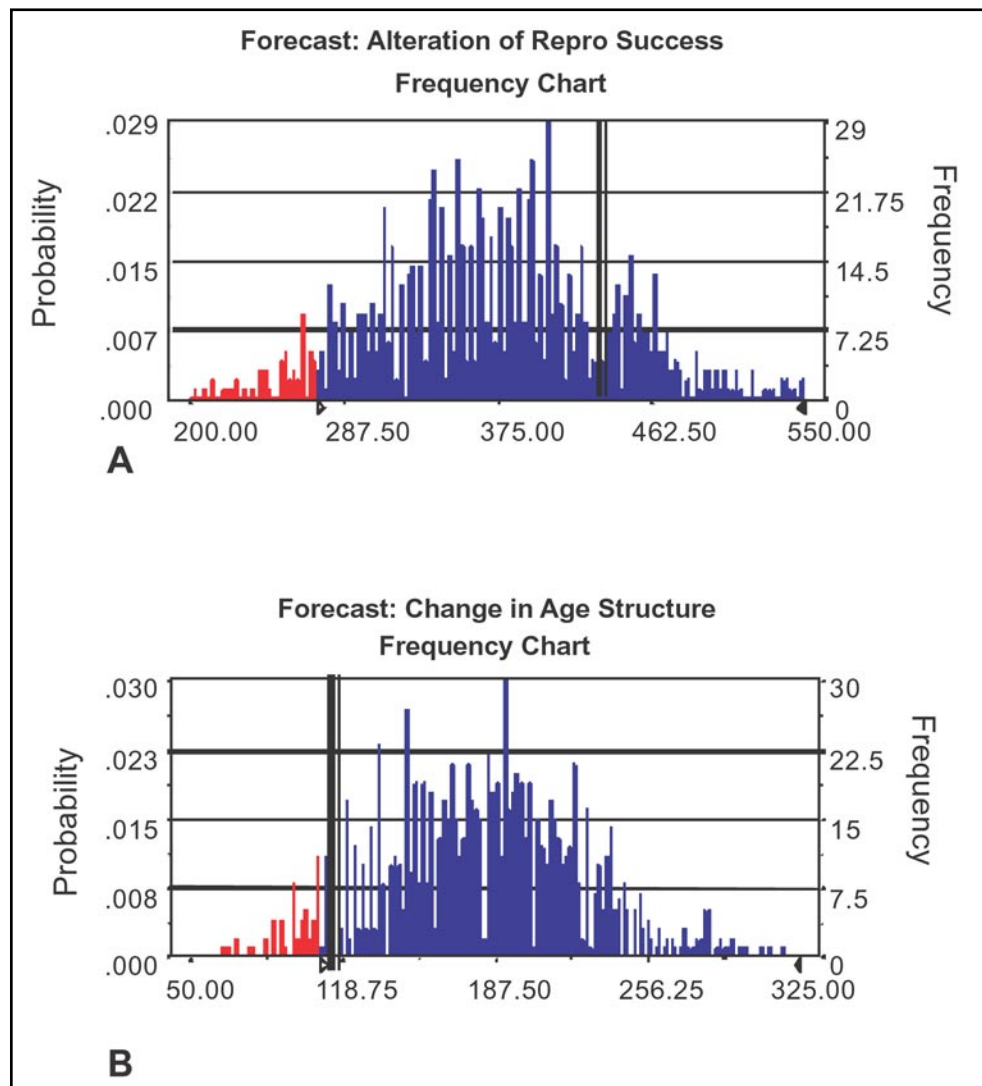
**Figure 4.** Distributions for the Forecast of two of the observed effects, alteration of reproductive success and change in age structure.

Invasive species provides a case with a low rank. Although invasive species do exist in the broad geographic region, there are not particular prevalent in the habitat used by Pacific herring. However, the lack of evidence may also be due to the instance that there has not been an extensive survey for these types of organisms within the region. So the initial ranking and the one given the source is a 2 but a rank of zero and a rank of 4 are given equal probabilities.

After the ranks are assigned for each source and stressor and the linkages are assigned an uncertainty, then the Monte Carlo computation is performed. The output is a distribution as portrayed in Figure 4.

In these figures the calculated value for the retrospective assessment is marked as solid line. In Figure 4a it can be seen that the distribution is generally below the original estimate, indicating that the original may have been an overestimate of the true risk. Figure 4b compares the original estimate for risk to the change in age structure to the distribution and the original seems to be an underestimate of the degree of risk involved. Note that the risk scores for decline of the population are higher than that of age structure. This is because a change in age structure is one of the factors that are incorporated into the overall population decline.

One of the advantages of the WoE approach using Monte Carlo is that the process allows the examination of what factors within the model drive the final distribution of results. An improvement in the uncertainty associated with these factors should reduce the overall uncertainty of the estimates.
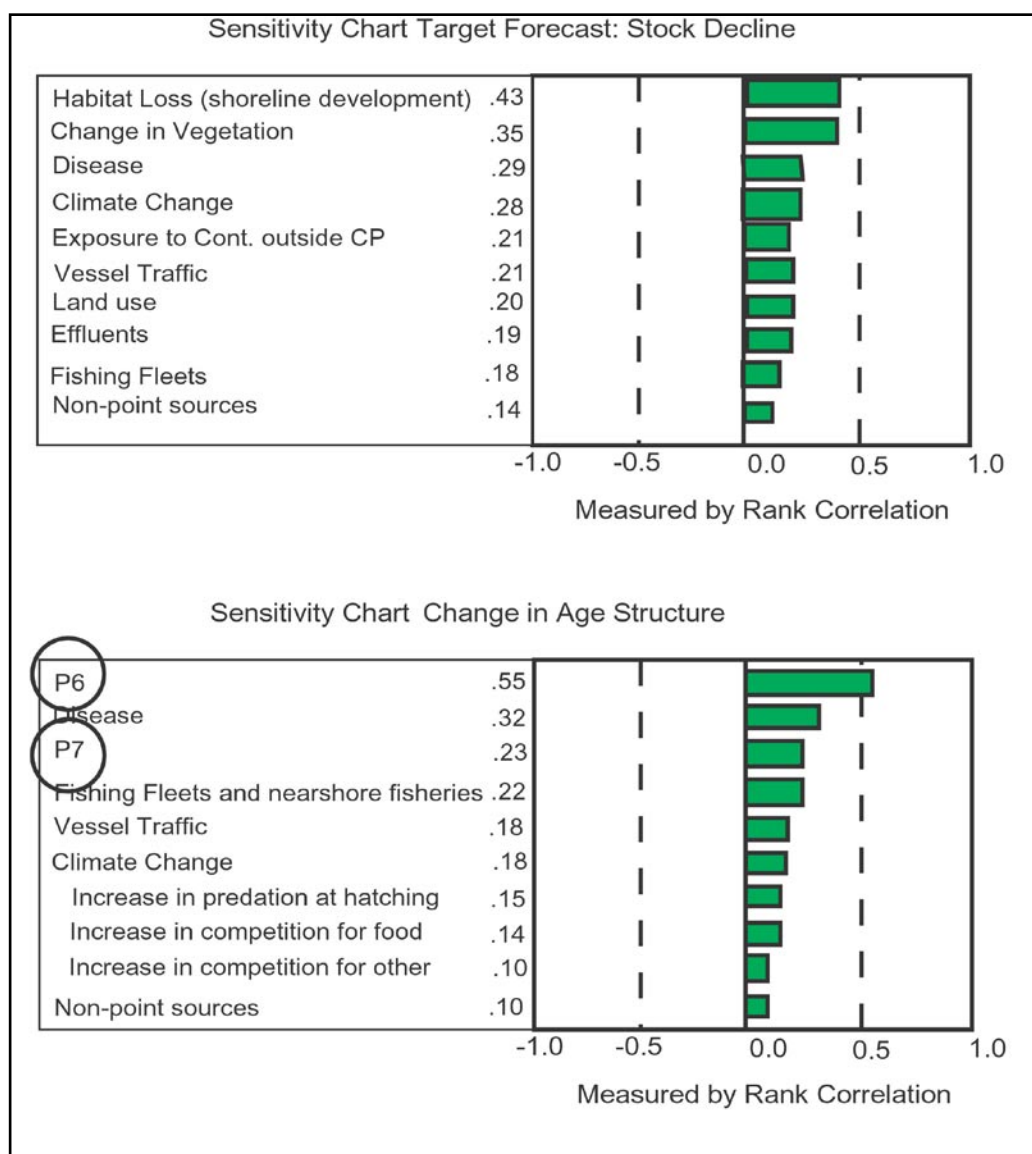
**Figure 5**. Sensitivity of the factors resulting in stock decline and the change in age structure.

Two examples are found in Figure 5. In the sensitivity chart for stock decline, habitat loss and change in vegetation both lead the sensitivity scores. Both factors have high ranks but also have a great deal of associated uncertainty. Note that climate change received a relatively low sensitivity score although it has a high rank. This is because there is little doubt that the PDO occurs and that it can have important effects so that the input distribution was very narrow. Input factors with low uncertainty are essentially constants and are not a cause of variability in the output.

In the chart ranking sensitivity for the change in age structure, two of the linkages between stressors and effects, P7 and P6 have a high sensitivity. This sensitivity is due to the fact that many of the mechanisms tying the impacts of contaminants to alterations in age structure are unclear. These linkages were given equal probability of tying a stressor to an effect and have a resultant high sensitivity score.

## Conclusions and Recommendations
The WoE approach coupled with a Monte Carlo analysis of the uncertainty proved useful and led to a series of conclusions:

- The declines observed at Cherry Point and the age structure common to Puget Sound stocks are due to large scale events, such as habitat loss and the PDO.

- Contaminants are possibly an important stressor, but there is considerable uncertainty in the linkage of toxicity to changes in age structure and population decline at large scales.

- A WoE approach can incorporate a variety of stressors and pathways and is based upon the diagnostic symptoms observed in the spawning stocks.

- It is possible to incorporate uncertainty in the rankings and the linkages into the description of the WoE estimate.

- The WoE combined with uncertainty analysis approach is flexible and new stressors and linkages can be easily added or subtracted as evidence is accumulated.

## Acknowledgements

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